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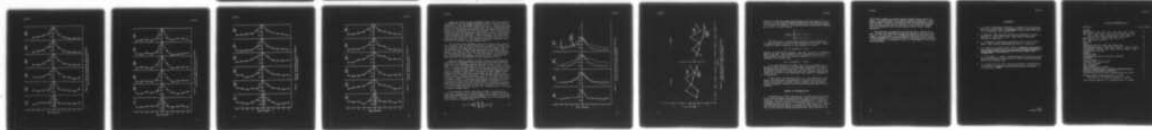
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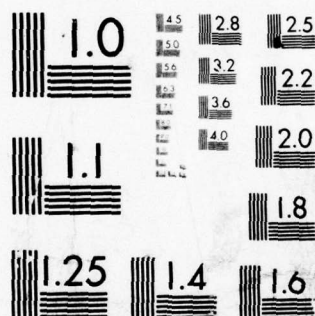
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NUSC Technical Report 5731



**Vertical Spatial
Correlation of
Reverberation in
Shallow Water -- Mode
Enhancement Techniques
(METS) as a Means To
Improve Echo Detection**

**Louis A. King
Wolfgang Bachor
Ralph W. Carone
Special Projects Department**



24 May 1978

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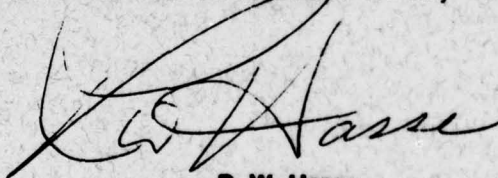
PREFACE

This study was accomplished under NUSC Project No. A-650-09, "Shallow Water Acoustic Theory and Measurements for Sonar Design and Operation," Principal Investigator, Dr. L. A. King (Code 3122), and Navy Subproject and Task No. SF-52-552-702-14054. The sponsoring activity is the Naval Sea Systems Command (SEA 06H1-4), A. Franceschetti, Program Manager.

The Technical Reviewer for this report was Dr. D. M. Viccione.

Mr. Wolfgang Bachor was assigned to NUSC as a West German Exchange Scientist from Erprobungstelle der Bundeswehr 71 (E-71), located in Eckernforde, Federal German Republic. His assignment was up in October 1976 and has since returned to his duties at E-71.

REVIEWED AND APPROVED: 24 May 1978

A handwritten signature in dark ink, appearing to read 'R. W. Hasse', is written over a horizontal line.

R. W. Hasse
Head: Special Projects Department

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Although the uniform and cosine configurations produced higher correlation values than did the single transducers, they fell below 0.5 for spacings greater than 2 m. By assuming echoes that consist primarily of mode 1 or mode 2 and applying Mode Enhancement Techniques (METS) to a receiving array of six elements uniformly spaced 2 m apart, we see that the array gain is computed to be 3.0 and 7.8 dB, respectively. The example of METS indicates that appreciable array gains can be achieved with vertical arrays operating in shallow water.

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VERTICAL SPATIAL CORRELATION OF REVERBERATION IN SHALLOW WATER —
MODE ENHANCEMENT TECHNIQUES (METS) AS A
MEANS TO IMPROVE ECHO DETECTION

INTRODUCTION

The processing gain of current shipboard sonar systems designed for deep water diminishes if the systems are subjected to the multipath conditions of shallow-water areas. However, a concept is being explored, based on normal-mode theory, that may regain the loss in performance and even optimize system performance in shallow water. This concept, termed Mode Enhancement Techniques (METS),¹ is based on modal properties of sound propagation that can be used to enhance both transmitted and received signals. In order to explore METS and determine processing gains against reverberation, a series of Shallow Water Echo and Reverberation Experiments (SWERE) was initiated.

In September 1975, one such experiment was conducted in 30 m of water in a shallow-water acoustic range located between Block Island, Rhode Island, and Fishers Island, New York. Supporting geophysical data affecting sound propagation in the range, such as bottom profile and bottom composition, have been documented.² Environmental data, such as wind speed and direction, were obtained from a weather station on Block Island, and the sound-speed profiles were measured during each event. Propagation and reverberation data were obtained using a vertical array of transducers.³ Associated switching electronics allowed the array to be used for both transmitting and receiving operations.

Pulses of fixed shape (continuous wave (CW) pulses) at a carrier frequency of 1700 Hz were transmitted using the following four different source configurations:

1. S1, a single transducer located near the surface of the water column;
2. S13, a single transducer located in the middle of the water column;
3. UNIFORM, an array of 11 transducers, uniformly spaced, whose input signal amplitudes were equal; and
4. COSINE, an array of 11 transducers, uniformly spaced, whose input signal amplitudes were given a cosine weighting according to depth in the water column.

The vertical sound-pressure field generated by each of the configurations was measured with hydrophones suspended from a ship stationed at various fixed increments of range. Concurrently, measurements were made of the reverberation produced by each configuration. The reverberation field was sampled simultaneously at 11 different depths.

The received signals were reduced and analyzed to provide the following data:

1. The intensity of reverberation and signal versus range,
2. The intensity of reverberation and signal versus depth, and
3. The spatial correlation of reverberation in the vertical direction at six range (or time) increments 0.75 km apart.

The first two data sets have been presented in another report.⁴ It is the vertical correlation of reverberation as a function of range and hydrophone spacing that is addressed here. An application of METS is made, based on the results, to demonstrate how the vertical correlation of reverberation may be used in the METS context for improving detection in shallow water.

DATA ACQUISITION

The physical arrangement for the experiment is shown in figure 1. The normal-mode tower³ of the Block Island/Fishers Island (BIFI) range and its related transmit and receive electronic equipment were used during the test to generate and measure reverberation. Basically, the tower is a vertical array of 25 transducers, spaced approximately 1 m apart, that can be configured electronically in different arrangements to transmit and receive acoustic signals. For transmitting, the four different configurations listed above were chosen. Eleven transducers, numbered 8 through 18, located along the middle section of the tower, were selected for receiving. This provided a 10 m receiving aperture covering the middle third of the water column. The individual outputs of all 11 hydrophones were recorded simultaneously for later analysis of both intensity over a period of time and phase information relative to the center transducer. For all four configurations, equal electrical power was supplied to normalize all results to the same amount of available acoustic energy. A pulse width of 200 ms was selected as a compromise between total energy transmitted into the water and reasonable range resolution. A carrier frequency of 1700 Hz was used to achieve optimum response in the transducers and connected electronic equipment. A repetition rate of 6 to 8 s was chosen to allow

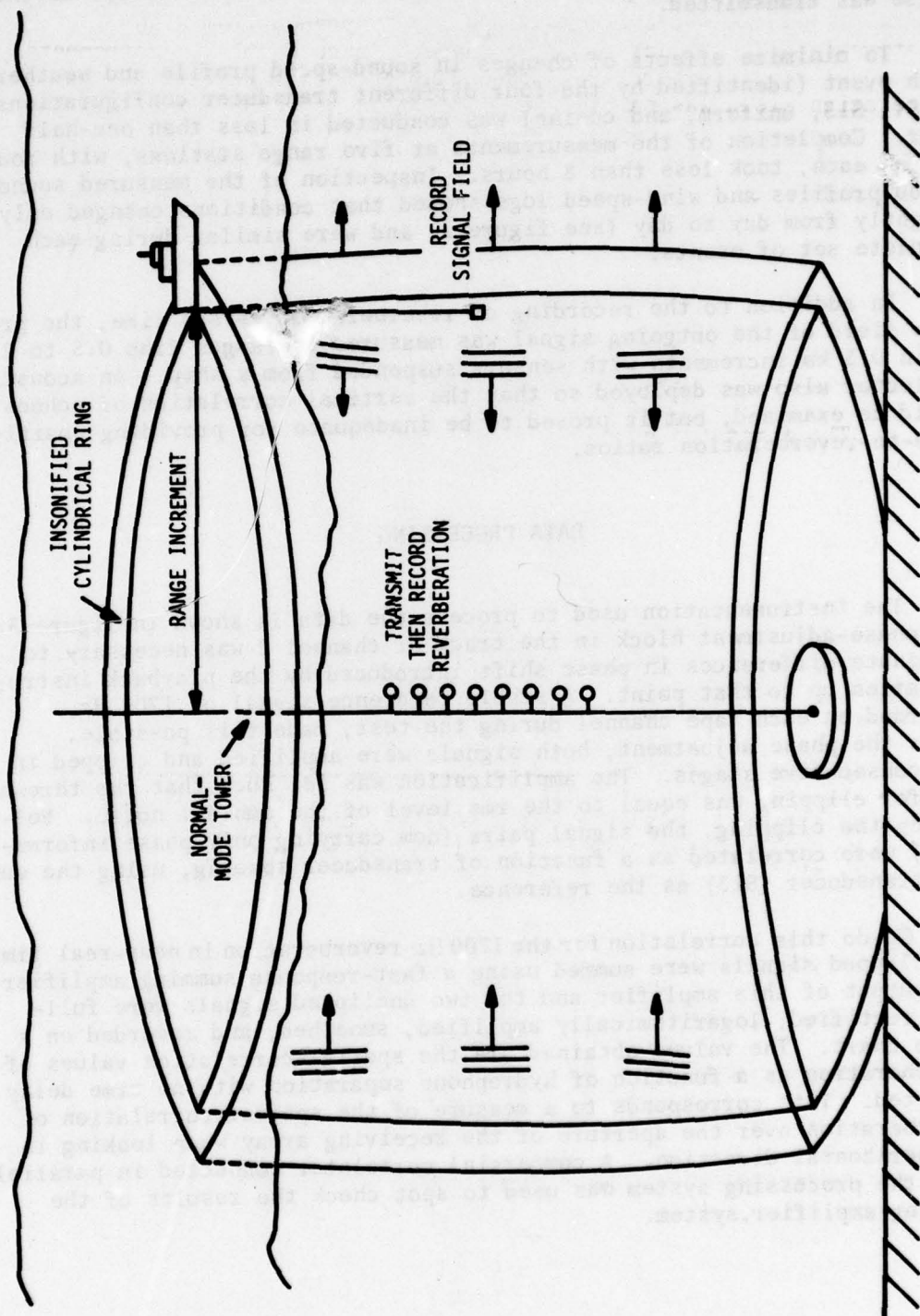


Figure 1. Physical Arrangement for the Experiment

each pulse to diminish to the actual ambient-noise level before another pulse was transmitted.

To minimize effects of changes in sound-speed profile and weather, each event (identified by the four different transducer configurations as S1, S13, uniform, and cosine) was conducted in less than one-half hour. Completion of the measurements at five range stations, with four events each, took less than 8 hours. Inspection of the measured sound-speed profiles and wind-speed logs showed that conditions changed only slightly from day to day (see figure 2) and were similar during each complete set of events.

In addition to the recording of reverberation versus time, the pressure field of the outgoing signal was measured at ranges from 0.5 to 2.5 km in 0.5 km increments with sensors suspended from a ship. An acoustic reflector also was deployed so that the vertical correlation of echoes could be examined, but it proved to be inadequate for providing positive echo-to-reverberation ratios.

DATA PROCESSING

The instrumentation used to process the data is shown in figure 3. The phase-adjustment block in the track of channel 2 was necessary to eliminate differences in phase shift introduced by the playback instrumentation up to that point. A stable reference signal of 1700 Hz, recorded on each tape channel during the test, made this possible. After the phase adjustment, both signals were amplified and clipped in two consecutive stages. The amplification was set such that the threshold for clipping was equal to the rms level of the ambient noise. Following the clipping, the signal pairs (now carrying only phase information) were correlated as a function of transducer spacing, using the center transducer (S13) as the reference.

To do this correlation for the 1700 Hz reverberation in near-real time, the clipped signals were summed using a fast-response summing amplifier. The output of this amplifier and the two unclipped signals were full-wave rectified, logarithmically amplified, smoothed, and recorded on a strip chart. The values obtained are the spatial-correlation values of reverberation as a function of hydrophone separation with no time delay inserted. This corresponds to a measure of the spatial correlation of reverberation over the aperture of the receiving array when looking in the horizontal direction. A commercial correlator connected in parallel with the processing system was used to spot check the results of the summing-amplifier system.

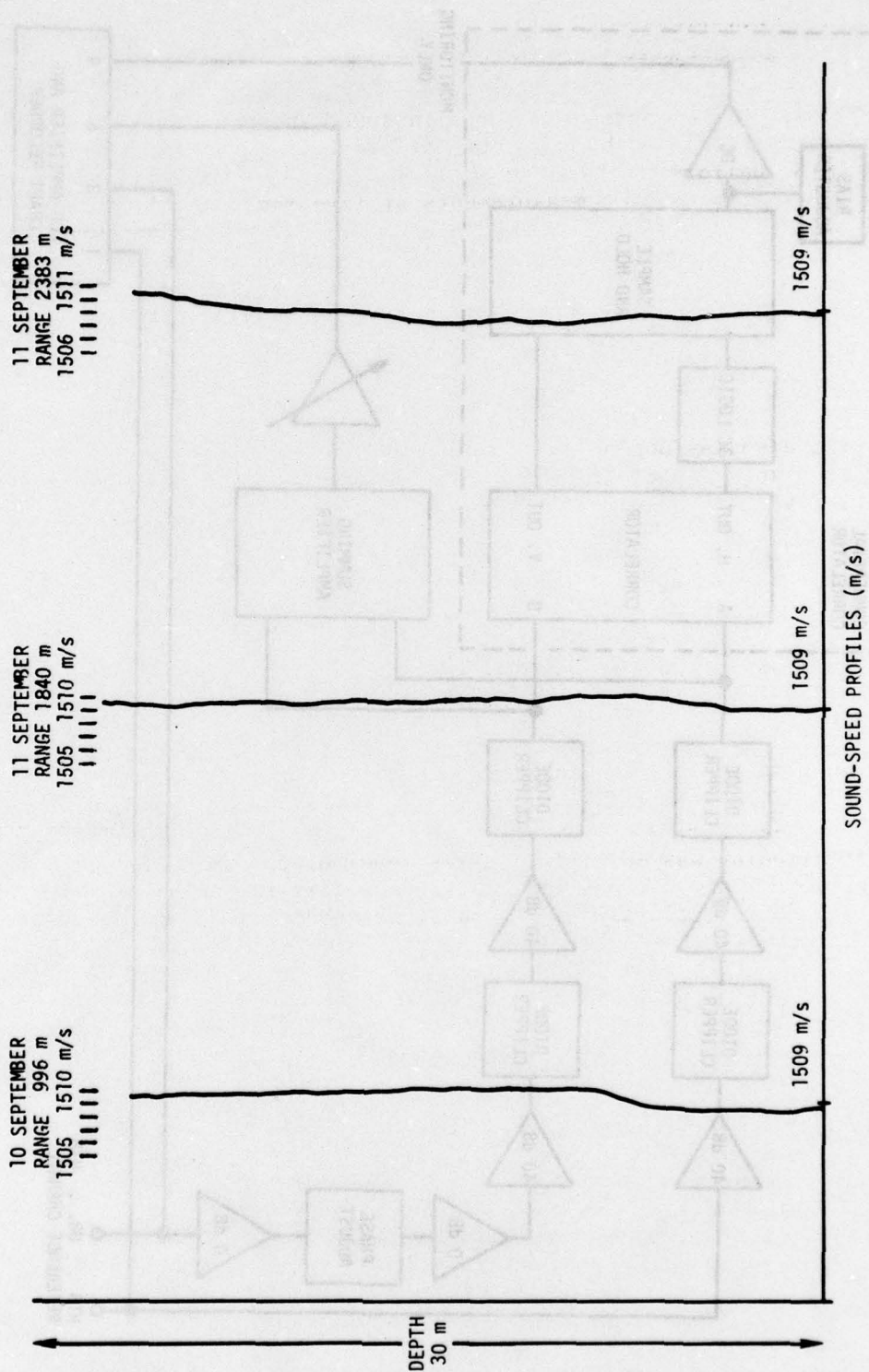


Figure 2. Typical Sound-Speed Profiles

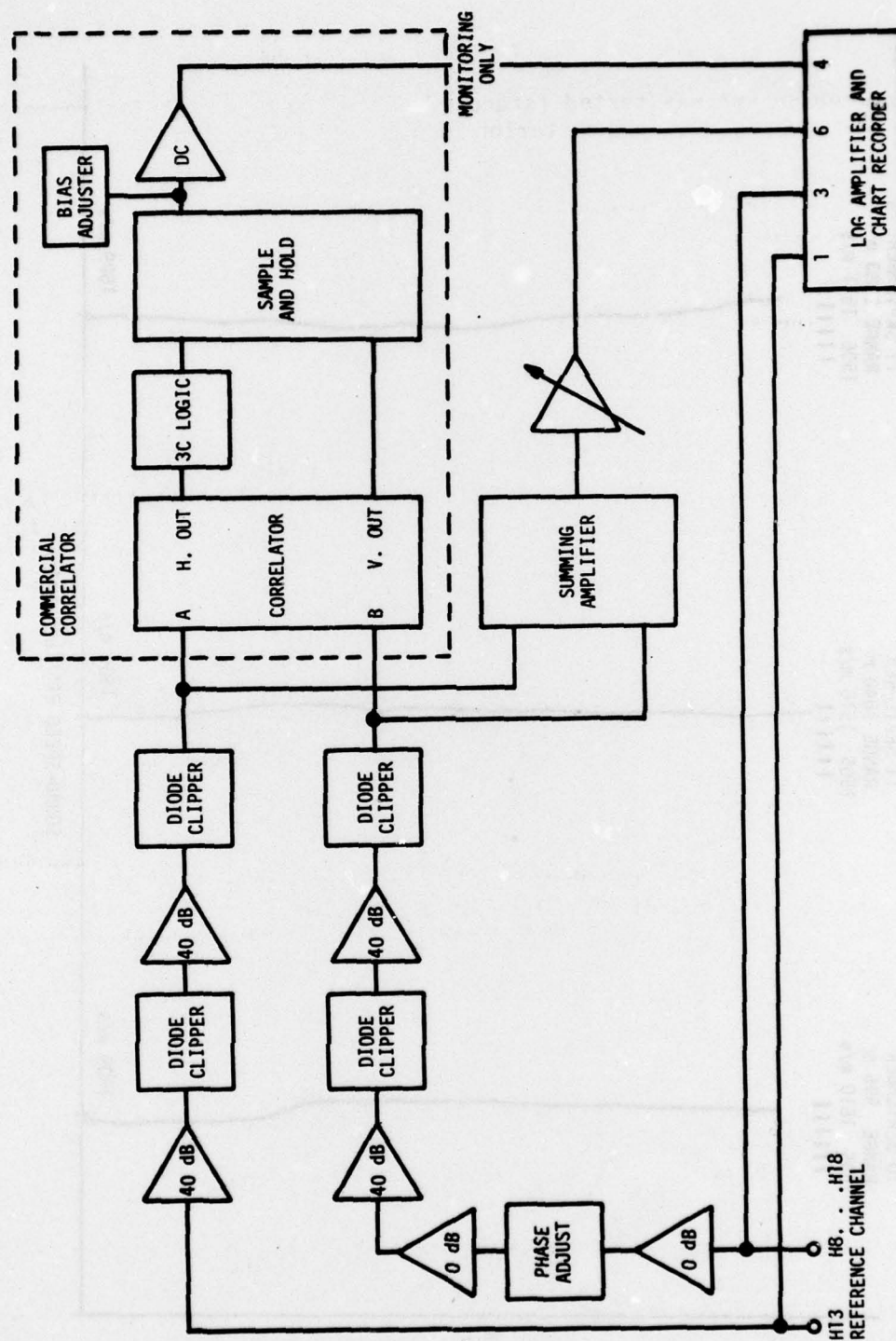


Figure 3. Block Diagram of Correlator System

The pulse statistics are derived from a typical set of five consecutive pulses observed within the stream of pulses that were transmitted. The five-pulse set was tested (standard deviation to mean) for representativeness according to the criterion $sd/m < 1/2$ + an acceptable number, otherwise reject.

The sets of data, obtained as described above, were reduced further by sampling the smoothed waveforms of the crosscorrelation functions. Six groups of samples, each group 1 s apart, were obtained from each record of reverberation. Each group consisted of five values, spaced 10 ms apart. The six 1-s intervals correspond to one-way range increments of 0.75 km over a range from 0.75 to 4.5 km. The mean and standard deviation of each five-sample group were used as indicators of the variability in the crosscorrelation at the associated range. When the ratio of the standard deviation to the mean was greater than one-half, little confidence was placed in the mean value of correlation for that range, since any trend in the mean values in such cases could have resulted from the sampling procedure alone. These statistics were examined for two pulses of each event. (An event consists of five consecutive pulses obtained on a pair of hydrophones.) Additional analysis also was made of the mean and standard deviation for corresponding time samples of the correlation from pulse to pulse for five consecutive pulses. This standard deviation indicated the variability in correlation from pulse to pulse introduced by a changing medium. Again, the ratio of standard deviation to mean was used to determine confidence in any trend in the mean values.

Correlation values ($|\rho|$) were plotted as a function of range to form a scatter diagram for each hydrophone spacing and configuration. Ten such scatter diagrams of correlation values, one for each hydrophone pair, represent one event. Five samples per range for five consecutive pulses produce a cloud of 25 values at each range. The mean value for each cloud ($\langle |\rho| \rangle$) was obtained and plotted versus the hydrophone spacing. Figures 4 through 7 show curves of the resulting average values of the vertical correlation of reverberation ($\langle |\rho| \rangle$) as a function of hydrophone spacing for the S1, S13, cosine, and uniform configurations, respectively.

DISCUSSION OF RESULTS

The vertical correlation versus hydrophone spacing for the cosine and uniform weightings of the array are shown in figures 6 and 7, respectively. Comparison of the two reveals little difference. For convenience in further comparisons, the uniform weighting was taken as representative for the array case.

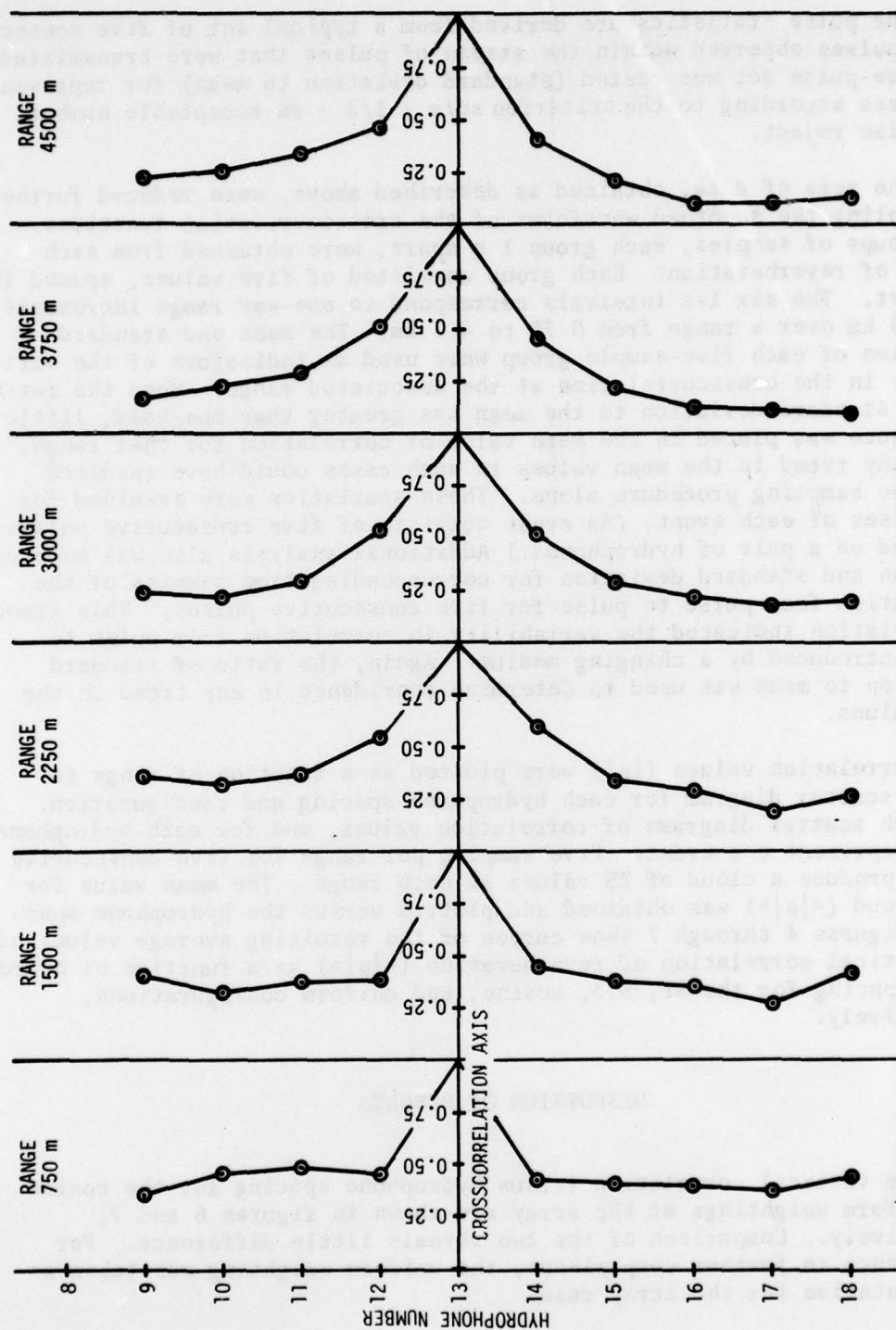


Figure 4. Vertical Correlation Versus Hydrophone Spacing, Near-Surface Transducer S1

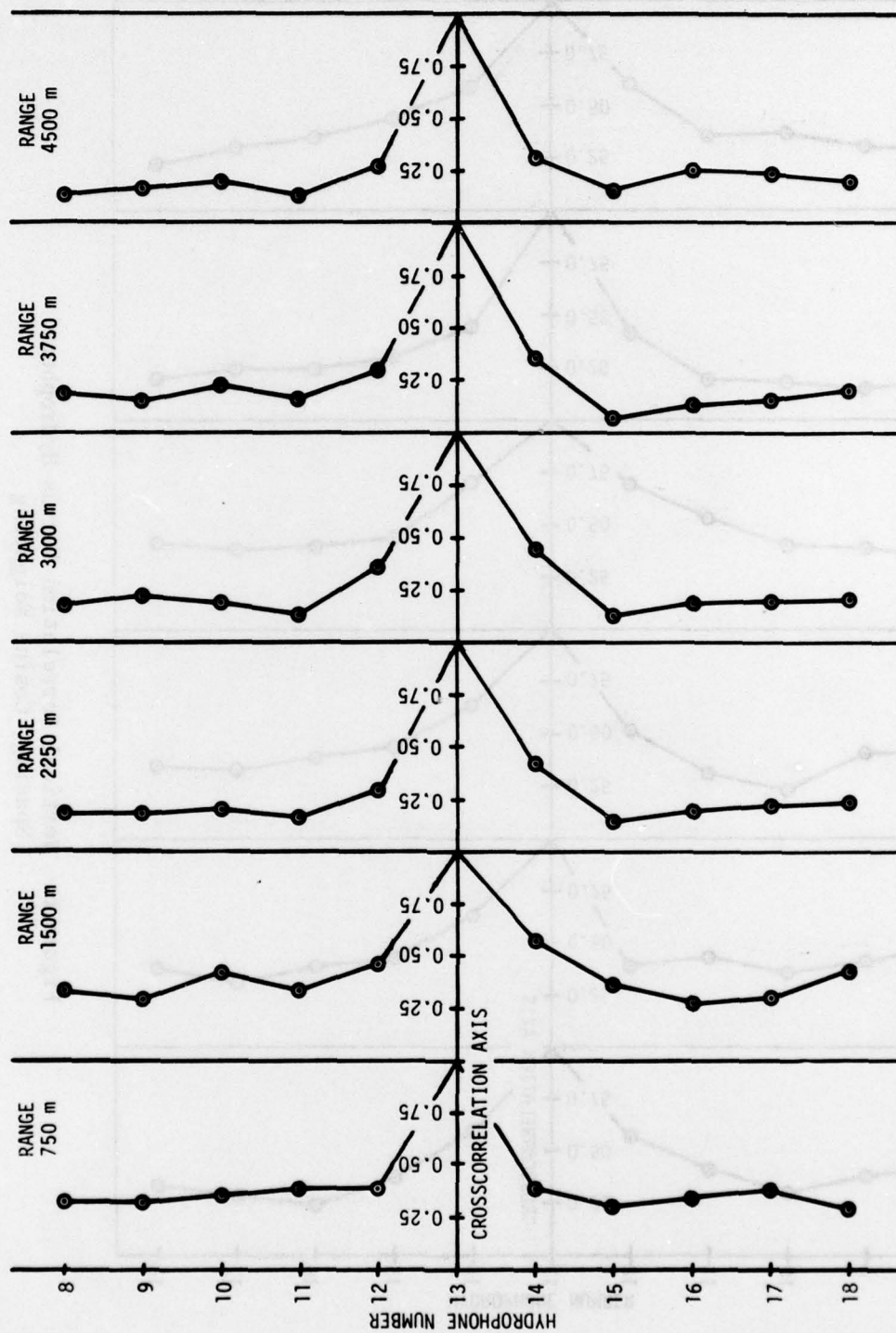


Figure 5. Vertical Correlation Versus Hydrophone Spacing, Middepth Transducer S13

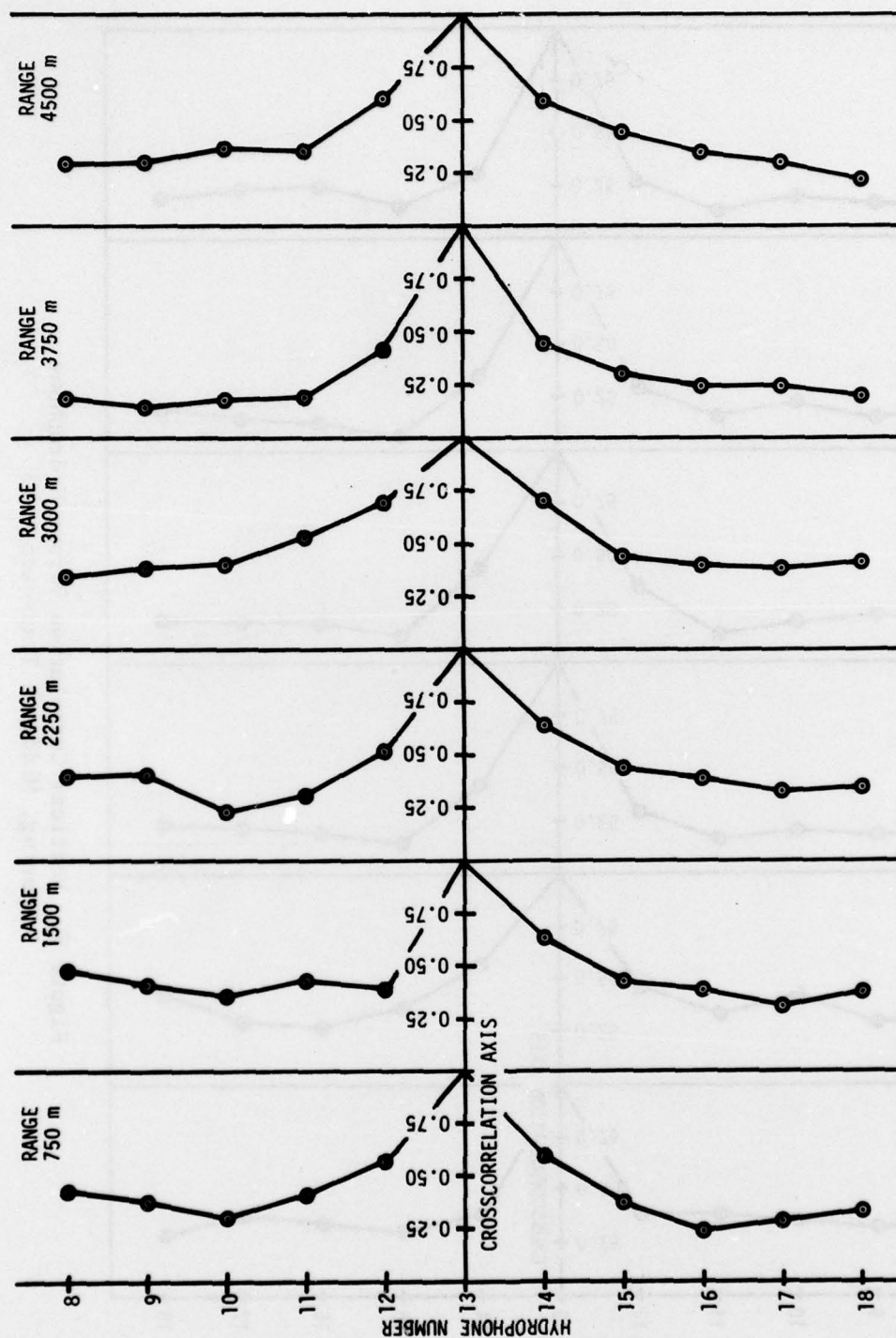


Figure 6. Vertical Correlation Versus Hydrophone Spacing, Cosine Weighting

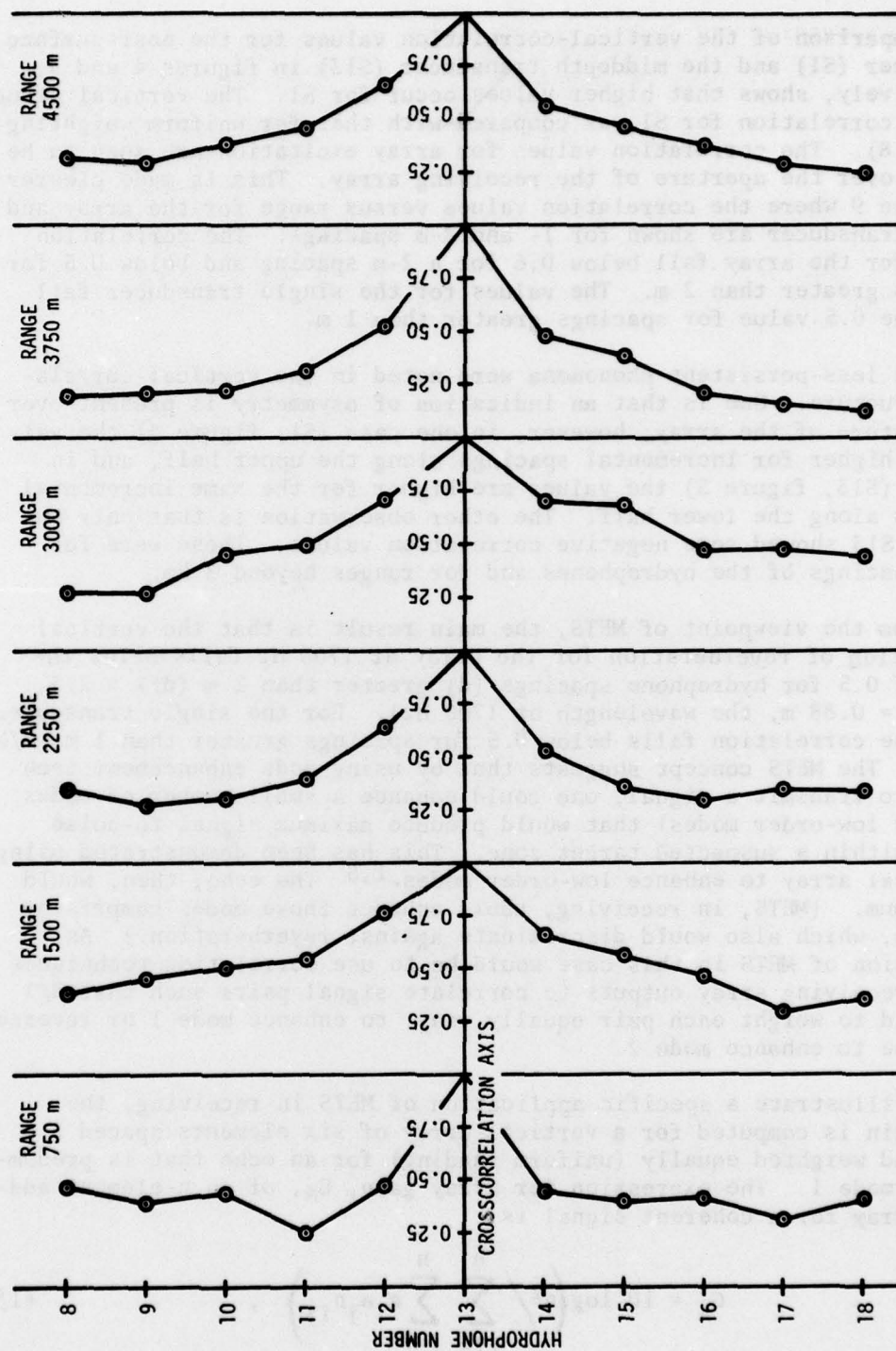


Figure 7. Vertical Correlation Versus Hydrophone Spacing, Uniform Weighting

Comparison of the vertical-correlation values for the near-surface transducer (S1) and the middepth transducer (S13) in figures 4 and 5, respectively, shows that higher values occur for S1. The vertical structure of correlation for S1 was compared with that for uniform weighting (figure 8). The correlation values for array excitation are seen to be greater over the aperture of the receiving array. This is made clearer in figure 9 where the correlation values versus range for the array and single transducer are shown for 1- and 2-m spacings. The correlation values for the array fall below 0.6 for a 2-m spacing and below 0.5 for spacings greater than 2 m. The values for the single transducer fall below the 0.5 value for spacings greater than 1 m.

Two less-persistent phenomena were noted in the vertical-correlation structure. One is that an indication of asymmetry is present over the aperture of the array; however, in one case (S1, figure 4) the values are higher for incremental spacings along the upper half, and in another (S13, figure 5) the values are higher for the same incremental spacings along the lower half. The other observation is that only the case of S13 showed some negative correlation values. These were for large spacings of the hydrophones and for ranges beyond 3 km.

From the viewpoint of METS, the main result is that the vertical correlation of reverberation for the array at 1700 Hz falls below the value of 0.5 for hydrophone spacings (d) greater than 2 m ($d/\lambda > 2.3$, where $\lambda = 0.88$ m, the wavelength at 1700 Hz). For the single transducer (S1), the correlation falls below 0.5 for spacings greater than 1 m ($d/\lambda > 1.1$). The METS concept suggests that by using mode enhancement techniques to transmit a signal, one could enhance a small number of modes (usually low-order modes) that would produce maximum signal-to-noise levels within a suspected target zone. This has been demonstrated using a vertical array to enhance low-order modes.^{1,5} The echo, then, would be maximum. (METS, in receiving, could enhance those modes comprising the echo, which also would discriminate against reverberation.) An application of METS in this case would be to use correlation techniques on the receiving array outputs to correlate signal pairs such that $d/\lambda > 2.3$ and to weight each pair equally, say, to enhance mode 1 or reverse the phase to enhance mode 2.

To illustrate a specific application of METS in receiving, the array gain is computed for a vertical array of six elements spaced 2 m apart and weighted equally (uniform shading) for an echo that is predominantly mode 1. The expression for array gain, G_A , of an n -element additive array for a coherent signal is

$$G_A = 10 \log \left(n^2 / \sum_{i=1}^n \sum_{j=1}^n a_i a_j \rho_{ij} \right), \quad (1)$$

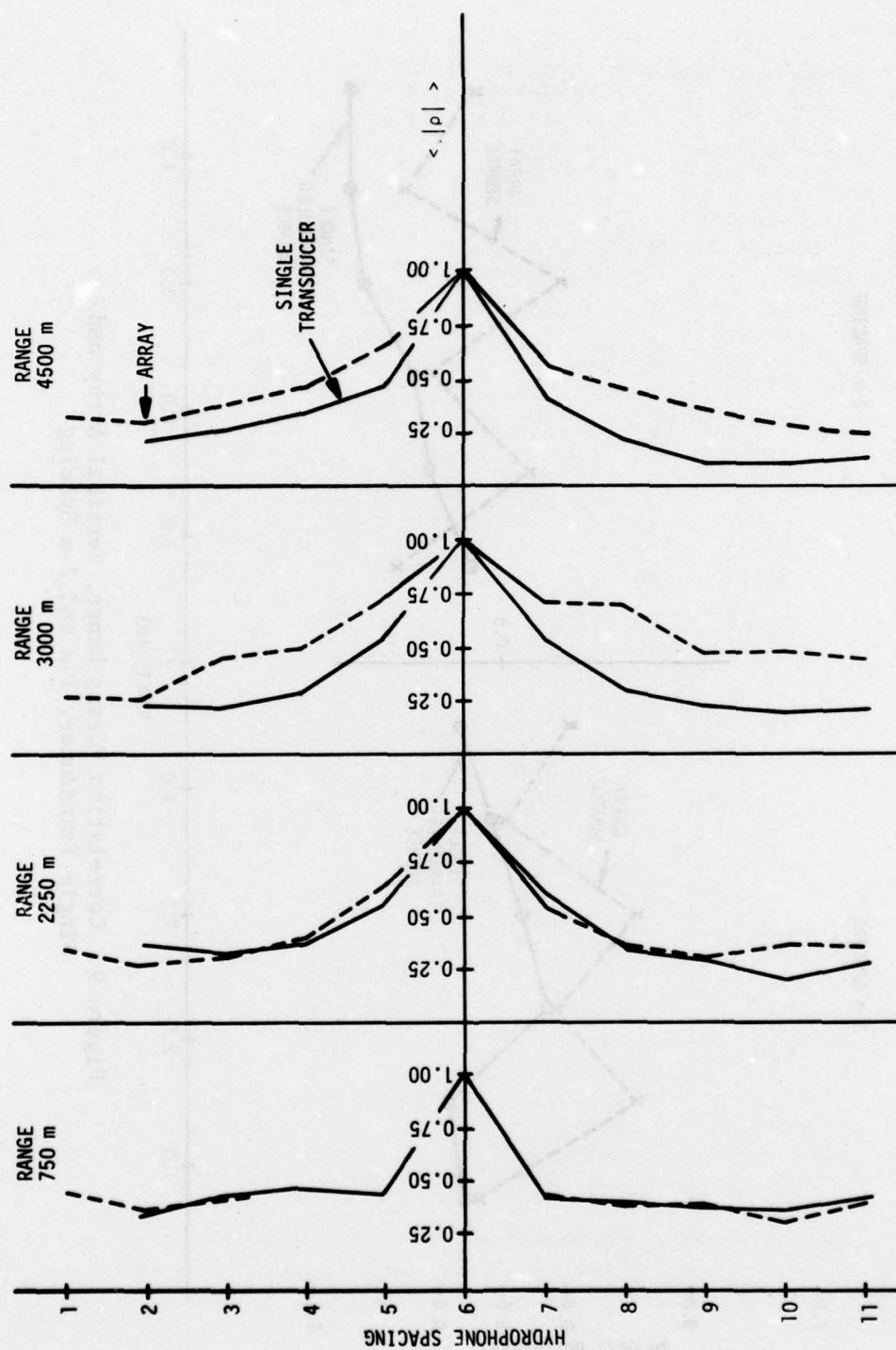


Figure 8. Vertical Correlation Versus Hydrophone Spacing, Vertical Array and Single Transducer

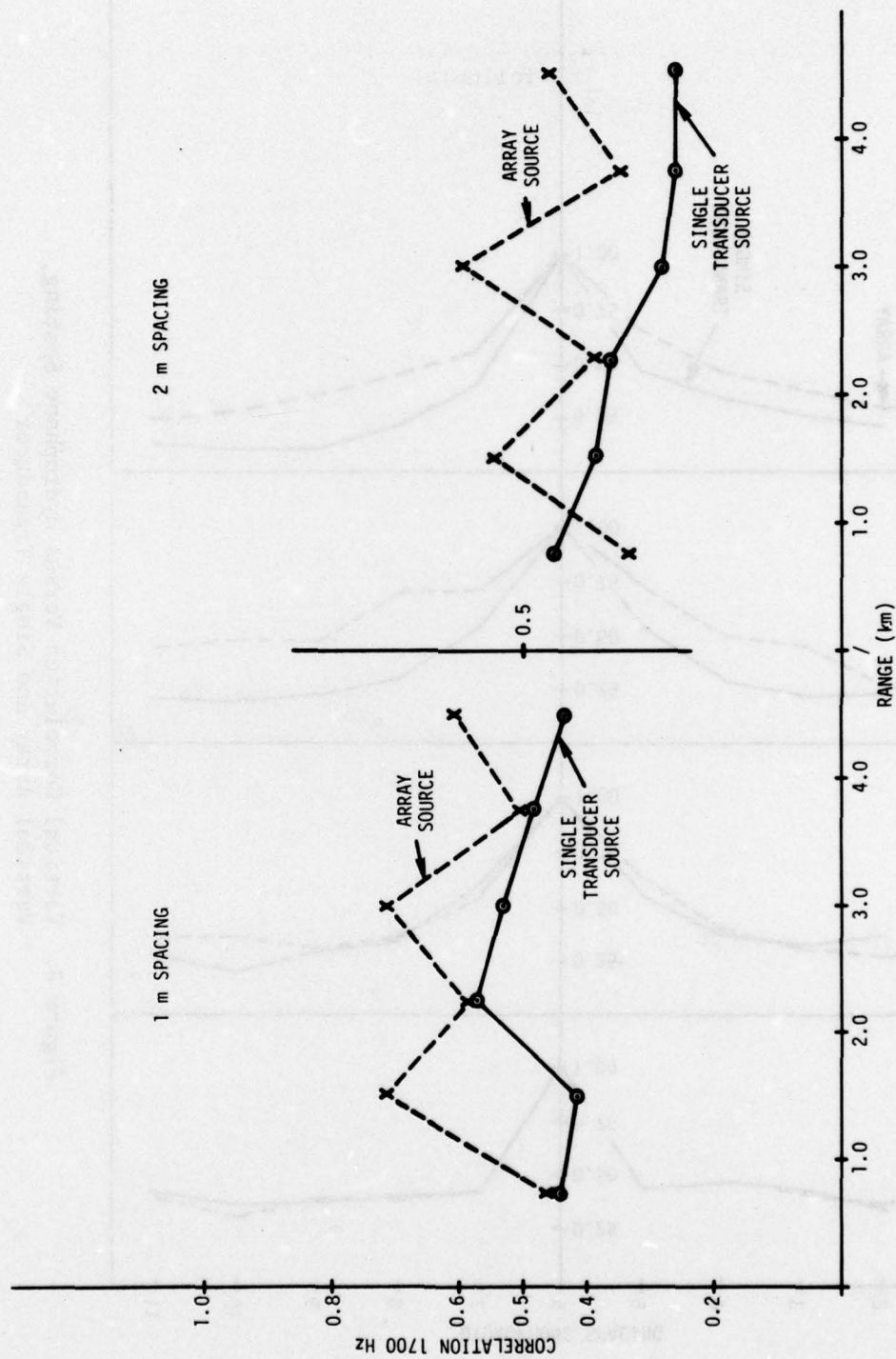


Figure 9. Correlation Versus Range, Vertical Array and Single Transducer, 1-m and 2-m Spacing

where a_i, a_j are the element shading factors (for this case, $a_i = a_j = 1$) and ρ_{ij} is the crosscorrelation coefficient of reverberation between the i -th and j -th elements. The following values are used for computing G_A : for $i, j = 1, 2, 3, 4, 5$, and 6 ,

$$a_i a_j \rho_{ij} = \begin{cases} 1 & i = j \\ 0.6 & |i - j| = 1 \\ 0.3 & |i - j| > 1 \end{cases}$$

The value of 0.6 is the maximum correlation value obtained for a 2-m spacing (figure 9) and 0.3 is the correlation noise level. Substituting the values of equation (2) into equation (1) yields

$$G_A = 10 \log(36/18) = 3.0 \text{ dB}$$

Suppose, for demonstration purposes, that mode 2 should be a predominant mode in the echo. Then, one-half of the six-element array would be reverse-phased, such that the element weightings a_i are (1,1,1,-1,-1,-1). Equation (1) would then yield

$$G_A = 10 \log(36/6) = 7.8 \text{ dB}$$

It is seen from this one example that, with a six-element array having an overall length of 10 m, appreciable improvement in signal to reverberation levels can be achieved. This indication is contrary to the general conclusion of Urick and Lund⁶ that extremely long vertical arrays are required to yield appreciable gains against a background of reverberation.

To deal with a less idealized echo, i.e., one containing a mix of modes, the normal-mode field generated at the receiving array by the target (now acting as a source) would be computed, and the elements would be weighted to enhance the field and discriminate against reverberation.

SUMMARY AND RECOMMENDATIONS

Reverberation at 1700 Hz produced by a transmitting vertical array and a single transducer have been recorded using a vertical array of receivers. The vertical correlation of reverberation as a function of hydrophone spacing is shown to be uncorrelated for $d/\lambda > 2.3$ for the transmitting array and for $d/\lambda > 1.1$ for the single transducer. However, the transmitting array offers an advantage over the single sensor in that it can be used to enhance particular modes (modes favored by the

shallow-water channel) to produce greater signal-to-noise levels at a target. By applying METS to an array of receiving hydrophones so that selected modes of the echo are enhanced while the reverberation components are not, as shown for the case $d/\lambda > 2.3$, we note that greater echo-to-reverberation levels can be achieved than by using a single transducer.

The observation presented here are derived from a limited set of data. However, the indications warrant the support of additional investigation. In particular, it is recommended that additional validation of METS improvements be obtained by means of additional spatial correlation measurements of reverberation, as well as measurements of the signal field and echoes.

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